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Magnetic Design of Mirror Magnet Based on Fermilab's Nb_3Sn Cos-theta Coils

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Introduction

The tests of few high field dipole models based on the cos-theta Nb_3Sn coils (HFDA02-04) revealed serious quench performance problems. In order to resolve those problems efficiently and in shortest time, reduction of magnet fabrication and test turnaround time and cost is extremely important. One of possible ways in this direction is a magnetic mirror magnet design. The mirror magnet uses only one half-coil assembled in the same mechanical structure as a real dipole model. The second half-coil is replaced with the half cylinder from low-carbon steel. Additional cost and time saving is achieved by using a two-piece bolted skin and re-utilizing the iron yoke and coil-yoke spacers. This note describes the mirror magnet magnetic design and summarizes its main parameters.

Magnetic design

The magnetic design of the mirror magnet was analyzed using OPERA2D code. The iron half-cylinder, which replaces one of the half-coils in the magnetic mirror magnet, was designed in such a way that there is a 2 mm gap between the coil mid-plane and the mirror which is necessary for the installation of the ground insulation and instrumentation (voltage taps, thermal and mechanical gauges, spot heaters, etc.). The iron mirror block has the non-linear magnetic properties similar to those for the iron yoke.

Figure 1 shows the magnet cross-section with the flux lines and flux density inside the iron at two currents - 2 kA and 20 kA.

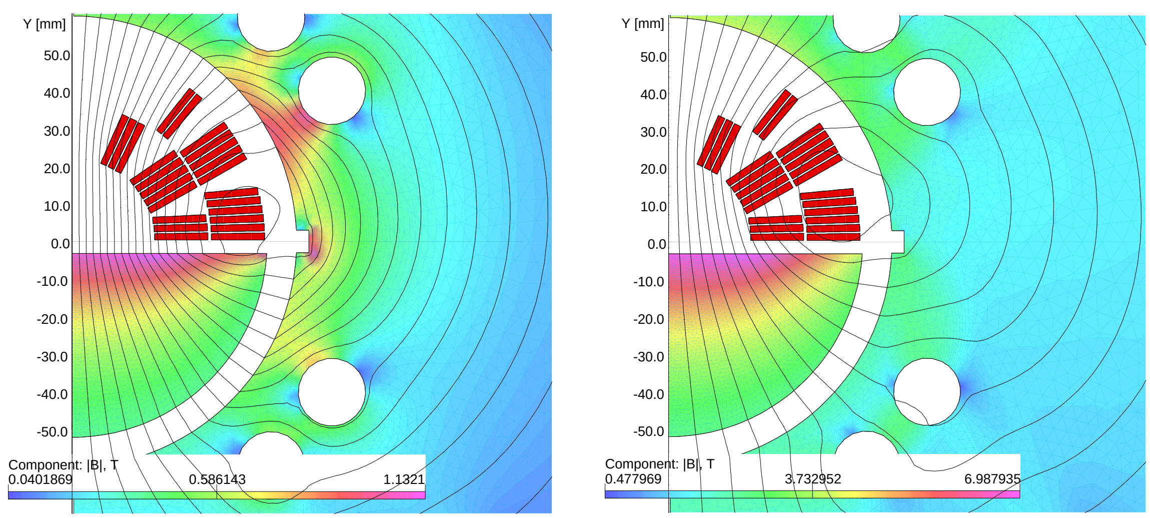

Figure 1. Field distribution in the mirror magnet at two currents:
I=2 kA – left, I=20 kA - right.

High magnetic permeability of the mirror at low fields enforces the dipole-like field distribution in the half-coil. At high fields, the saturation of iron changes the field distribution and magnet parameters.

Magnet parameters

The magnet load lines and transfer function are shown in Figures 2 and 3. Due to strong saturation of magnetic mirror there is a considerable difference between the bore central field (calculated at X=0, Y=0) and the peak field in the coil that reaches 30% at 20 kA current. The transfer function is also very non-linear, changing by a factor of 1.5 within 1-20 kA current range.

The magnet short sample limits were calculated for the critical current density in the strand non-Cu area varying in the range of 1000 A/mm^2 to 3000 A/mm^2. Figure 4 shows the quench field in the magnet bore center and the peak field in the coil as functions of the critical current density in strands at 12 T and 4.2 K. Thus, for the coils with the critical current density of 1800 A/mm^2, the maximum bore quench field reaches 8.4 T and the peak field in the coil reaches 11.2 T at the quench current of 25.0 kA. Figure 5 shows the inductance and stored energy for the mirror design in 0-10 T bore field range.

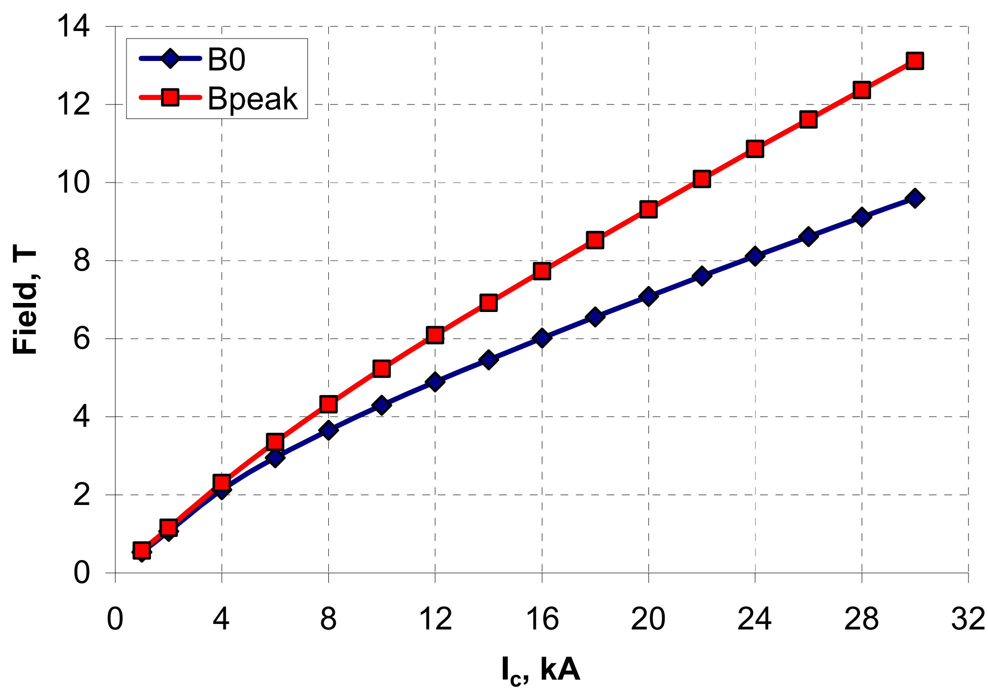

Figure 2. Mirror magnet load lines.

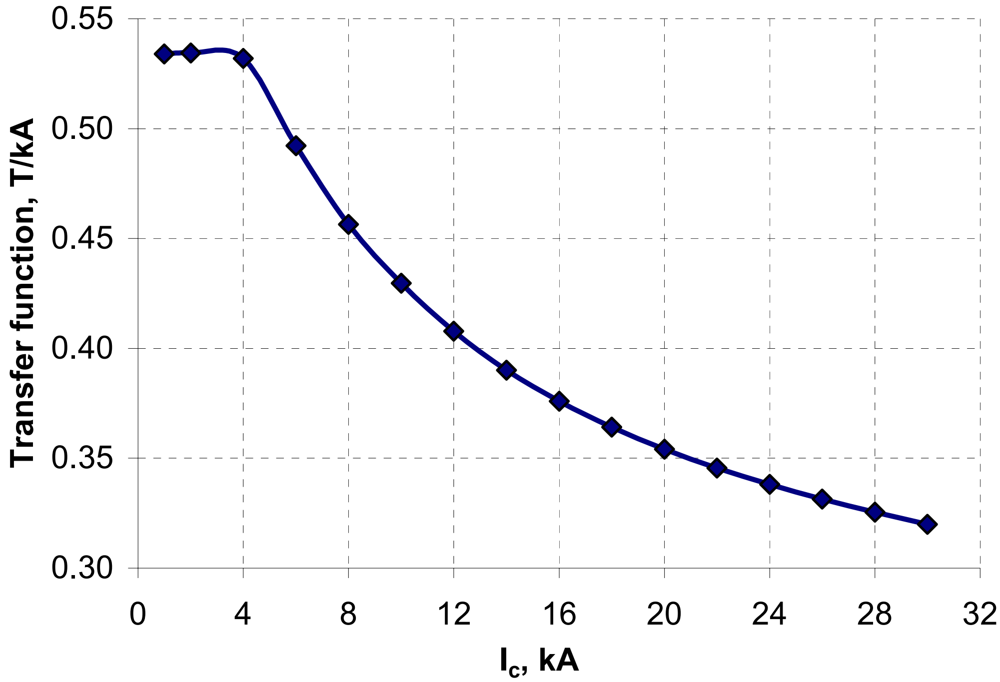

Figure 3. Mirror magnet transfer function.

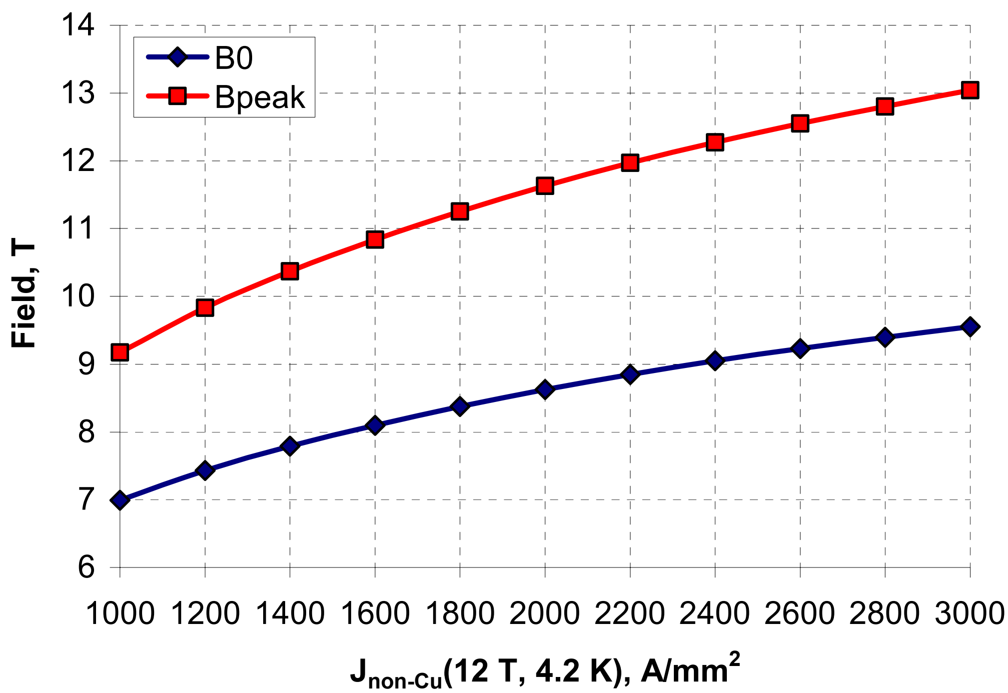

Figure 4. Quench fields: B0 – bore field (X=0, Y=0); Bpeak – maximum field in the coil.

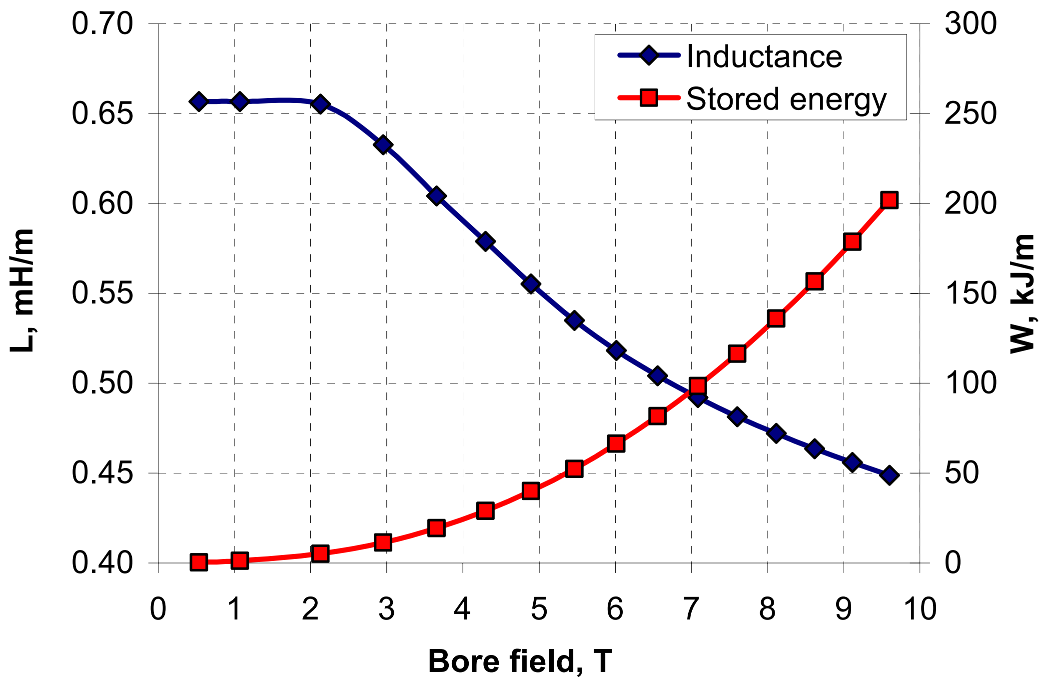

Figure 5. Mirror magnet inductance and stored energy.

The major magnet parameters are summarized in Table 1. The quench parameters were calculated for the critical current density in the coil (non-copper area) of 1800 A/mm^2 at 12 T and 4.2 K. There is considerable difference in Lorentz forces with respect to the "standard" configuration with two half-coils. Due to the flux deviations at high fields, a positive vertical force component acting on the coil midplane blocks virtually compensates the vertical force components from other blocks.

Table 1. Magnet parameters.

Parameter		Value
N turns		24
Quench field in the bore center, T		8.4
Quench field in the conductor, T		11.2
Quench current, kA		25.0
Transfer function @ quench, T/kA		0.334
Stored energy @ quench, kJ/m		146.3
Inductance @ quench, mH/m		0.467
Forces per first coil quadrant @ 20 kA, MN/m	Fx	1.73
	Fy	-0.16

Conclusions

The described design of the mirror magnet allows reducing the fabrication and test time and cost of Nb_3Sn cos-theta coils. As it follows from presented data, the magnet reaches high fields in the coil at high currents that will allow studying the coil mechanics and quench performance in the conditions similar to those in real magnets.